DERIVING ANALYTICAL RELIEF FUNCTIONS FOR SWITCHING VARIANTS AND ASSIGNING PRIORITY BY TRANSIENT ANALYSIS

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Abstract – Eventually, limit violations occur by the power systems operation, such as: voltage level at buses, loadings of transmission lines and power transformers, etc. If violations are detected in the supervision process, corrective measures may be carried out in order to eliminate them or to reduce their intensity. Loading restriction is an extreme solution and should only be adopted as the last control action. Previous researches have shown that it is possible to control constraints in electrical systems by changing the network topology, using a technique named Corrective Switching, which requires no additional costs. For solving problems related to the large number of switching variants to be analyzed for eliminating branch overloads, it will be presented methodologies based on circuit analysis to estimate current in branches after splitting bus-bars substations, using just a few linear calculations. After estimating the loading of these branches, the best switching variants will ordered in a priority list, ranked by the minimum transient disturbance. At least, results obtained by simulation in the IEEE Reliability Test System will be presented.

Keywords: Corrective Switching, Relief Functions, Transient Analysis.

1 INTRODUCTION

Limit violations, such as voltage level and loadings of transmission lines and power transformers may occur by power systems operation. If violations are detected, corrective measures must be carried out in order to mitigate them. Because of increasingly requirements on quality and continuity imposed to power utilities by the regulatory agencies, load shedding is an extreme solution and should just be adopted as the last control action. This way, control measures, such as active and reactive power rescheduling, phase shifters adjustments or even voltage control at generator units are usually adopted. These measures require in general increase of costs. Another way to avoid limit violations may occur by changing the network topology, adopting Corrective Switching.

Corrective Switching dates from the late 70's and consists in a tool for controlling power flow in electrical networks, changing its topology. According to this methodology, the control tools are on/off of switching of transmission lines, transformers or shunt elements, substation bus-bars coupling or splitting or yet rearrangement of branches connected to the bus-bars. It has been proved that, this way it is possible to change the state of power systems, influencing the distribution of power flow, the technical losses, the short-circuit level, and the voltage profile at the system. The main advantage of this control technique compared with the former ones is the economy, because its implementation depends on the operation of existing elements in the system, exclusively.

Over the past 30 years, some Corrective Switching algorithms were proposed with different applications: the objective of [1], [3]-[4], [6]-[10] was eliminate overloads in transmission lines; solve voltage problems at substation bus-bars was the purpose of [7]-[8] e [10]; increasing power system security was proposed by [5]. Furthermore, these algorithms were also different in a couple of proposed switching variants: switching on/off of transmission lines and transformers was proposed by [1]; switching of shunt elements; changing-over connections of branches and loads in substations bus-bars was explored by [3]-[4], [6]-[10].

If all N transmission elements of a power system may change its operational condition, the number of possible arrangements is 2^N. Considering also the possibility of changing the interconnection of these elements in substations bus-bars, the search space to be analyzed in order to obtain a feasible solution would be very broad, leading to a discrete multi-variable problem. Thus, most developed algorithms over the years consider different approaches to reduce the search space, such as: switching only in substations and transmission lines electrically close to the overloaded branch; discard combinations of variants belonging to different switching nodes; list of more probable effective arrangements for eliminating overloads in a specific branch, assigned off-line.

Despite the existing differences in philosophy of the proposed algorithms, the importance of the technique of Corrective Switching in Power Systems operation is mentioned in all works. In this context, the objective of all methodologies is the application in real time, providing subsidies to operators to eliminate eventual restrictions or to improve security. Furthermore, during expansion planning tasks, some reinforcements are required because of overloads. If corrective measures are found at this time these reinforcements may be in principle postponed, resulting in economy. It must be assured however that the corrective measures should be carried out on a time compatible with network security.

In order to apply Corrective Switching in Power Systems operation, the necessary simulations must be processed quickly. Just very promising variants should be tested by an exact load flow calculation, so that operators' decision in control centers will not be delayed. This way, a linearization of the solutions may be an attractive alternative, in order to provide estimates of loading changes due to switching measures. Firstly, such a method was presented in [4], [7]-[8], where Relief Functions were developed heuristically, based on experiments in real networks, for estimating current just in overloaded branches after bus-bar splitting in substations. In present work, equations were derived for estimating current after bus-bar splitting, in order to obtain estimates closer to the results provided by an exact load flow. Although a linear equations system is the background to derivations, the resulting expression has so few calculations as the former Relief Functions. Simulations have shown that the solution obtained using linear method developed is in average ten times faster than an exact load flow.

In order to test the effectiveness of the developed linear model, simulations carried out in IEEE Reliability Test System will be presented. The most promise switching variants are organized in a priority list to be tested by an exact load flow calculation. The classification order of these variants in the list was done in [7]-[8] according the ascendant value of the corresponding switching power. A further contribution of this proposal will be a ranking based on minimum transient disturbance caused by each switching variant, analyzed by the ATP - Alternative Transient Program. This is necessary because variants may be found, that cause transient disturbance with greater significance than their corresponding switching power.

This paper is organized as follows: section 2 presents a review of the linear method employed in this work. Section 3 introduces Relief Function methodology and shows the development of a Relief Function based on circuit analysis. In section 4, results are presented. At last, section 5 shows the conclusions.

2 LINEARIZATION USING BACKWARD INJECTION

For applying Corrective Switching technique in real time in power system operation, some linearizations of the equations that describe power system behavior have been proposed in order to enable a fast identification of the higher effective variants. This way, it has been developed in [3] a methodology based on current injection, named *Backward Injection*. For presenting this tech-

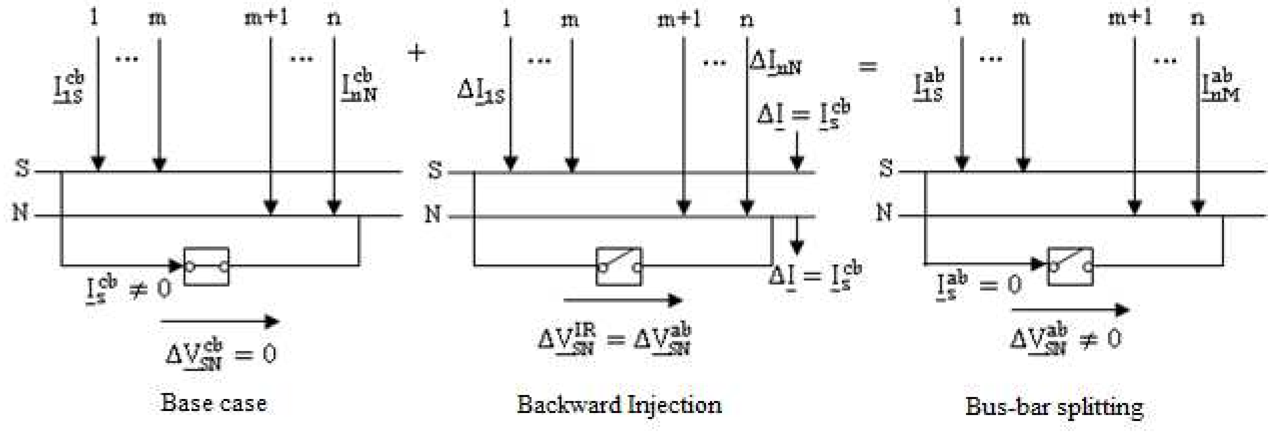


Figure 1: Bus-bar splitting simulation superimposing Backward Injection to base case.

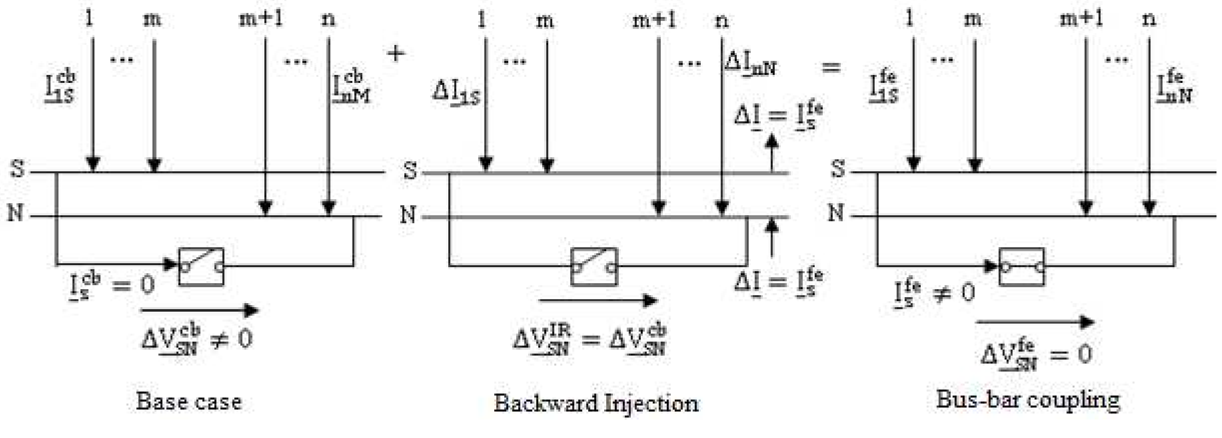


Figure 2: Bus-bar coupling simulation superimposing Backward Injection to base case.

nique, consider, as an example, the process of splitting and coupling two bus-bars in a substation, as illustrated in figures 1 and 2.

Figure 1 illustrates how bus-bar splitting can be simulated, starting from the base case and applying Backward Injection, using superposition. This figure shows three situations. First one is the base case, where n transmission lines exist interconnected to the coupled bus-bars S and N. In this case, $\underline{I}_s^{cb}$ is the current through the circuit breaker that link these bus-bars. For realizing Backward Injection, presented by the intermediary situation, a load is introduced at bus-bar N and a current supply at bus-bar S, where $\Delta\underline{I} = \underline{I}_s^{cb}$. Superimposing Backward Injection to base case, it obtains the final situation, where the bus-bars are splitted.

For presenting coupling between bus-bars S and N, figure 2 is adopted. There are three cases too. In base case, bus-bars S and N are splitted and current $\underline{I}_s^{cb} = 0$. For obtaining the final case, where the bus-bars are coupled, it is superimposed Backward Injection to base case. In intermediary situation, a load is introduced at bus-bar N and a current supply at bus-bar S, where $\Delta\underline{I} = \underline{I}_s^{fe}$. $\underline{I}_s^{fe}$ means current through the circuit breaker after coupling bus-bars S and N. The main computational effort is calculating voltage and currents from backward injection by solving (1). In (1), $\Delta\underline{I}$ refers to current variation between S and N bus-bars; $\underline{Y}_{ij}$ corresponds to i-j nodal admittance matrix element; $\Delta\underline{V}_i$ is voltage variation in all system buses after a switching measure.

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ -\Delta\underline{I} \\ \vdots \\ \Delta\underline{I} \end{bmatrix} = \begin{bmatrix} -1 & \underline{y}_{12} & \cdots & \underline{y}_{1S} & \cdots & \underline{y}_{1N} \\ 0 & \underline{y}_{22} & \cdots & \underline{y}_{2S} & \cdots & \underline{y}_{2N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \underline{y}_{S2} & \cdots & \underline{y}_{SS} & \cdots & \underline{y}_{SN} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \underline{y}_{N2} & \cdots & \underline{y}_{NS} & \cdots & \underline{y}_{NN} \end{bmatrix} \begin{bmatrix} \Delta\underline{I}_1 \\ \Delta\underline{V}_2 \\ \vdots \\ \Delta\underline{V}_S \\ \vdots \\ \Delta\underline{V}_N \end{bmatrix} \qquad (1)$$

All $\underline{Y}_{ij}$ elements belong to the nodal admittance matrix. All loads and injections as constant active and reactive power were discarded. The additional condition that voltage at slack node remains constant ($\Delta\underline{V}_1 = 0$) is also modeled in (1). In case of splitting bus-bars S and N, $\Delta\underline{I}$ is the switching current that is equal to $\underline{I}_s^{cb}$, shifted by 180^o.

It is noteworthy that a model for bus-bars coupling using Backward Injection has been detailed in [11]. In [12], another way for modeling bus-bars coupling using results obtained by short-circuit theory for applying in Backward Injection was proposed. It was mentioned in [12]-[13] that, for bus-bar coupling, the computational effort using short-circuit theory combinated with Backward Injection is lower than using Just the last one. In this work, it will be presented in section results, a comparison between these methods.

The procedure for bus-bar splitting based on Backward Injection was developed in [3]. In [4], [7]-[8], this procedure was improved incorporating Relief Function methodology, based on heuristical analysis, for estimating loadings of branches that were overloaded before bus-bar splitting, considering just active power effects. This work will present a linear model, based on circuit analysis that considers the effects of reactive power in current estimates after bus-bar splitting.

3 BUS-BAR SPLITTING

Initially, it will be presented the methodology showed in [4], [7]-[8], using Relief Functions developed by sensibility analysis for estimating branch loading, previously overloaded, after bus-bar splitting in a substation. After, it will be developed, by means of circuit analysis, analytical derivation for estimating the loading of branches after bus-bar splitting.

3.1 Effects of bus-bar splitting according to Relief Function methodology

The first method to show a reduction in the number of switching variants in a substation is detailed in [2], and is kept in [3]-[4], [7]-[8]. It was shown in [2] that even in bulk power systems, just a few substations are feasible to mitigate overloads on a specific branch. These substations are known as switching nodes and can be obtained by rerouting the overload. Switching nodes are that ones where a substantial part of the rerouted overload flows.

Figure 3 illustrates power flow in a representation of a power system equivalent, where it is shown an overloaded branch A-B and a switching node S with its bus-bars interconnected by a closed circuit breaker. In this figure, P_{rat} corresponds to the rated power of the branch, ΔP_{ov} means the branch overload, ΔP_{re} refers to the rerouted power, P_S is the switching power, ΔP^s_{re} refers to the part of ΔP_{re} flowing to node S and ΔP^v_{re} is the part of ΔP^s_{re} flowing through the circuit breaker.

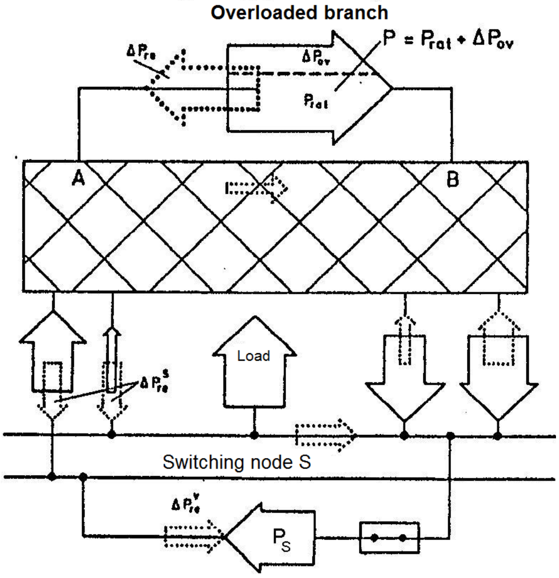


Figure 3: Representation of a power system equivalent for simulating overload rerouting with bus-bars coupled.

Loading on branch A-B is $P = P_{rat} + \Delta P_{ov}$. In order to eliminate the overload, it is necessary to reroute power in opposition to P, such as: $\Delta P_{re} > \Delta P_{ov}$. This procedure is sketched by dotted arrows in figure 3. It produces power redistribution in all network branches. According to [7], the loading of branch A-B after switching variant realization can be estimated from redistribution of rerouted power according to (2) and (3). For (2) and (3), P_{est} refers to estimated loading of overloaded branch, after opening circuit breaker, P means loading of overloaded branch on base case and F_r is the Relief Function.

$$\begin{cases} P_{est} = P - F_r \cdot \Delta P_{ov} & (2) \\ F_r = -P_S \cdot \Delta P_{re}^S \cdot \Delta P_{re}^V / \Delta P_{ov}^3 & (3) \end{cases}$$

A relief function must satisfy following conditions:

- If the realization of a switching variant results in ΔP^V_{re} in opposition to P_S, it will contribute to a relief of the overload. This variant is named relief variant;
- For a switching variant, if P_S, ΔP_{ov}, ΔP^S_{re} and ΔP^V_{re} are approximately equal, the realization of that one reduces the loading of overloaded branch to a value close to rated power of this element;
- Variants with very small ΔP^V_{re} must have a very large switching power P_S, in order to cause an appreciable relief.

Therefore, for eliminating overloads on branches, it is necessary to search variants that produce an estimated loading up to 100% of rated power of these elements. These variants are ranked in a priority list according to increasing switching powers, P_S, among all variants with corresponding estimated loading less or equal 100%. Thus, the first switching variant to be tested is the one with lower P_S. This procedure reduces the possibility of other branches become overloaded, also eliminating superfluous calculation of load flow. Thus, the goal to be reached by using relief functions is the estimating of branch loading with minimum number of calculation, avoiding superfluous computational effort, if one considers the huge number of switching variants in real networks.

3.2 Analytical derivation for simulating the effects of bus-bar splitting in a substation

In previous section, it was presented a model developed in [4], [7]-[8], based on Relief Functions, for estimating the loading of a branch A-B after splitting coupled bus-bars in a substation. However, presented model discarded reactive power influence in branch loading A-B.

For developing the analytical derivation to estimate effects of bus-bar splitting in a substation, it is necessary to change the representation of overloaded branch. It was done in [11] and is presented in figure 4. In this new configuration, it is introduced a new bus-bar A' closed to bus-bar A, with a current supply equals to current on branch A-B. In bus-bar A, it is represented a load equals to current on this same branch.

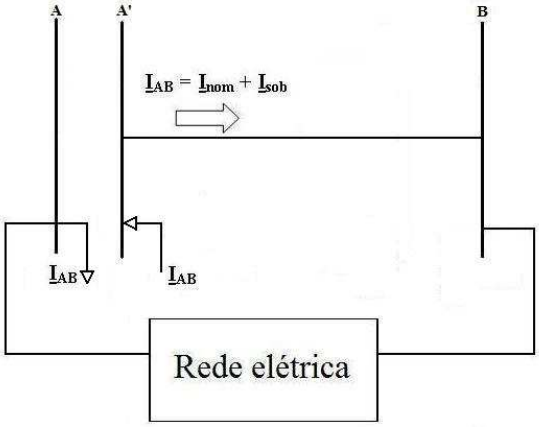


Figure 4: Representation of a power system equivalent with an overloaded branch modeled by the new methodology.

To eliminate the violation on branch A-B, it is injected, in bus-bar A, the part of overload on this branch. In bus-bar A', it is represented a load equals to overload on branch A-B. This procedure can be viewed in figure 5.

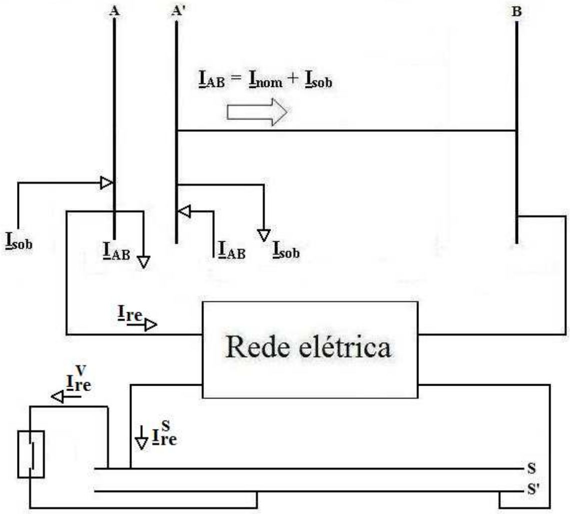


Figure 5: Power rerouting on branch A-B using new model.

According to figure 3, rerouted power will flow through some power system bus-bars, where some ones will be full contemplated and others just with a part of this rerouted power. Using circuit analysis, the part of power in switching node S is obtained and the loading on branch A-B after realization of a switching variant too. Consider the circuit presented in figure 6, where it is necessary to calculate impedances $\underline{Z}_{der}$, $\underline{Z}_{ser}$, $\underline{Z}_P$ e $\underline{Z}_{switch}$, since it is known $\underline{I}_{re}$ (rerouted current), $\underline{I}_{re}^S$ (part of $\underline{I}_{re}$ flowing to switching node S), $\underline{I}_{re}^V$ (part of $\underline{I}_{re}^S$ flowing through the circuit breaker that links bus-bar S and S'), $\underline{Z}_{AB}$ (impedance on overloaded branch), $\underline{V}^{re}_{AA'}$, e $\underline{V}^{re}_{A'B}$.

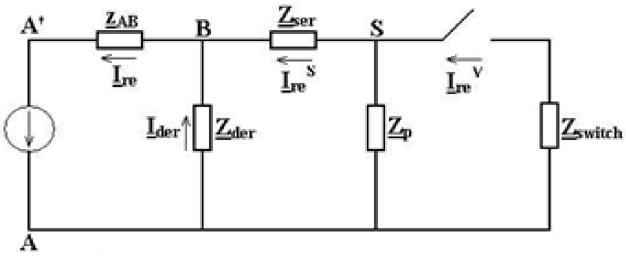


Figure 6: Representation of overload rerouting using circuit analysis.

Since current $\underline{I}_{re}^{S}$ represents a part of $\underline{I}_{re}$, it is presented by (4):

$$\underline{I}_{re}^{S} = k \cdot \underline{I}_{re} \tag{4}$$

In (4), k represents the part of rerouted power flowing to switching node S. Analyzing the circuit composed by the nodes A, A' e B, $\underline{Z}_{der}$ is calculated using (5).

$$\underline{Z}_{der} = -\frac{\underline{V}_{A'A}^{re} + \underline{Z}_{AB} \cdot \underline{I}_{re}}{\underline{I}_{re} \cdot (1-k)} \tag{5}$$

For calculating impedance $\underline{Z}_{ser}$, the circuit analyzed is composed by nodes B, S e A, where (6) is obtained.

$$\underline{Z}_{ser} = \frac{\underline{V}_{SA}^{re} - \underline{V}_{BA}^{re}}{k \cdot \underline{I}_{re}} \tag{6}$$

According to (7), current flowing through $\underline{Z}_{switch}$ is obtained using current divisor between this impedance and $\underline{Z}_{P}$ one.

$$\underline{I}_{re}^{V} = \frac{\underline{Z}_{P}}{\underline{Z}_{P} + \underline{Z}_{switch}} \cdot \underline{I}_{re}^{S} \tag{7}$$

Using circuit composed by nodes B, S e A', it obtains (8).

$$\frac{\underline{V}_{BA}^{re}}{\underline{I}_{re}^{S}} = -\left(\underline{Z}_{ser} + \frac{\underline{Z}_{P} \cdot \underline{Z}_{switch}}{\underline{Z}_{P} + \underline{Z}_{switch}}\right) \tag{8}$$

For calculating $\underline{Z}_{P}$ and $\underline{Z}_{switch}$, (7) and (8) are developed, where (9) and (10) are obtained.

$$\begin{cases} \underline{Z}_{switch} = \dfrac{-\left(\dfrac{\underline{V}_{BA}^{re}}{\underline{I}_{re}^{S}} + \underline{Z}_{ser}\right)}{\underline{I}_{re}^{V} / \underline{I}_{re}^{S}} & (9) \\ \underline{Z}_{P} = \dfrac{-\left(\dfrac{\underline{V}_{BA}^{re}}{\underline{I}_{re}^{S}} + \underline{Z}_{ser}\right)}{1 - \left(\underline{I}_{re}^{V} / \underline{I}_{re}^{S}\right)} & (10) \end{cases}$$

Since impedances of circuit in figure 5 are known, current on branch A-B after switching variant realization is calculated using circuit described in figure 7.

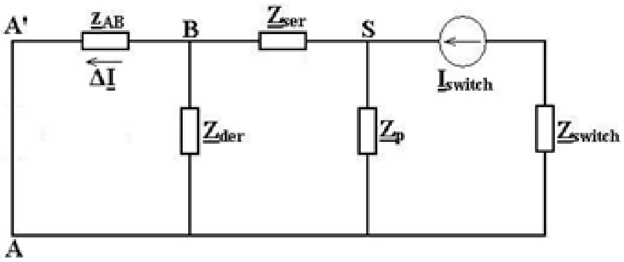


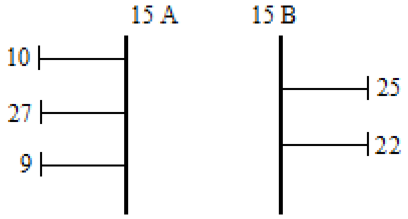
Figure 7: Representation of current estimate on branch A-B after switching variant realization.

In this circuit, $\underline{I}_{switch}$ is current flowing through the circuit breaker that links bus-bars on switching node S. This current is obtained from load flow calculation on base case. Current variation on branch A-B after switching variant realizations is calculated by (11).

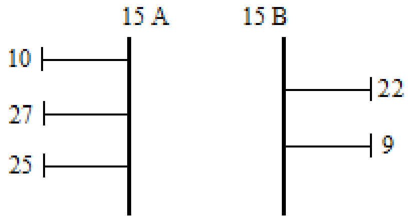
$$\begin{cases} \Delta\underline{I} = \dfrac{\underline{Z}_{der}}{\underline{Z}_{der} + \underline{Z}_{AB}} \cdot \dfrac{\underline{Z}_{P}}{\underline{Z}_{P} + \underline{Z}_{1}} \cdot \underline{I}_{switch} & (11) \\ \underline{Z}_{1} = \underline{Z}_{ser} + \dfrac{\underline{Z}_{der} \cdot \underline{Z}_{AB}}{\underline{Z}_{der} + \underline{Z}_{AB}} & (12) \end{cases}$$

4 RESULTS

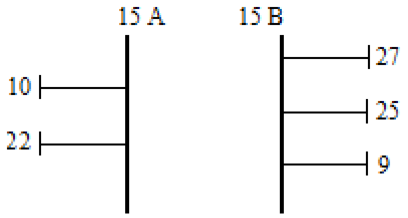
In order to illustrate the application of the derived Relief Function, the IEEE Reliability Test System was used. An overload of 18% on the branch 15-22 is caused by the outage of branch 26-21. Rerouting the overload, according to [3], five promising switching nodes are obtained, among which two are first-order and three are second order. Analyzing firstly variants of first-order switching nodes, because of lower switching currents, five variants of node 15 were selected. These are sketched in figure 8(a)-(e).



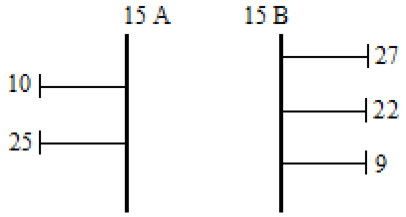
(a) Variant 1



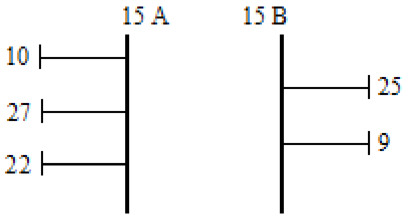
(b) Variant 2



(c) Variant 3



(d) Variant 4



(e) Variant 5

Figure 8: Promising variants according to estimated final loading of branch A-B.

Table 1 presents exact and estimated currents in overloaded branch 15-22 after realization of each one of switching variants presented in figure 8, in addition to I_{switch} obtained before splitting bus-bar 15. According to the criterion based on Switching Power (I_{switch}) established in [7]-[8], variants are ranked according to the order presented in last column of table 1.

Variant	I_{exact} (A)	$I_{estimated}$ (A)	I_{switch} (A)	Ranking of variants
1	1005	1210	1354	4
2	756	894	1307	3
3	1210	1207	354	1
4	1153	1218	1443	5
5	1094	1236	531	2

Table 1: Estimated currents by the derived relief function for five variants of node 15, in addition to ranking of variants based on I_{switch}.

Simulating the realization of the variants presented in figure 8 using ATP, the most significant ratios of transient voltages (after and before switching) for each one of nodes interconnected to switching node 15 are presented in table 2, for the most susceptible node. In this table, it is presented another ranking of variants based on minimum transient disturbance.

(*) $V_{after\_switching}/V_{before\_switching}$

Variant	Maximal overvoltage ratio (*)	Ranking of variants
1	1.473 (22)	5
2	1.163 (22)	3
3	1.024 (15B)	1
4	1.391 (15A)	4
5	1.144 (15A)	2

Table 2: Estimated currents by the derived relief function for five variants of node 15.

This way, according to tables 1 and 2, the first variant to be tested by an exact load flow is variant 3. After testing this variant in steady state, no constraints are obtained and this variant can be adopted.

5 CONCLUSIONS

According to the obtained results one concludes firstly that the size of the switching current is not determinative of the electromagnetic transient that is developed after conducting a switching measure. Furthermore, the most susceptible node, by all tested variants, was the switching node.

Another important conclusion is that the current of the previously overloaded branch may be estimated by means of few calculations according to the relief function presented in this paper. The main advantage of this function in comparison to the formers is the way it was obtained. An analytically derived function provides more confidence to the user as a heuristically one. Moreover, tests carried out by exact load flow calculation showed that estimated and exact loadings were very close, mainly for the most promising variants.

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